

Constructive role of non-adiabaticity for quantized charge pumping

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Abstract. We investigate a recently developed scheme for quantized charge pumping based on single-parameter modulation. The device was realized in an AlGaAl-GaAs gated nanowire. It has been shown theoretically that non-adiabaticity is fundamentally required to realize single-parameter pumping, while in previous multi-parameter pumping schemes it caused unwanted and less controllable currents. In this paper we demonstrate experimentally the constructive and destructive role of non-adiabaticity by analysing the pumping current over a broad frequency range.

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Pumping transport mechanisms have attracted much interest as an alternative means to generate charge and spin currents in the absence of a bias voltage. The pumping current results from periodic modulation of certain system parameters of a nanostructure connected to leads. Of particular interest has been the quantized regime when the current varies in steps of $e \cdot f$ as a function of the system parameters, where e is the electron charge and f is the frequency of modulation.

Much effort has been devoted to the adiabatic regime, when the variation of the parameters is slow compared to relaxation times of the system, and current quantization has been achieved almost 20 years ago [1]. Recently, a scheme has been developed in which only one parameter is varied [2, 3] and therefore non-adiabaticity is an essential requirement to achieve pumping [4]. In this regime the system is driven out of equilibrium, which was previously considered to counteract the quantized regime [5]. In the following we will demonstrate both, the destructive and constructive role of non-adiabaticity, depending on the pumping frequency f .

The device is similar to those used in [3]. A schematic is shown in Fig. 1(a) and the corresponding potential landscape $U(x)$ along the channel in (b). It was realized in an AlGaAs/GaAs heterostructure. A 700 nm wide constriction with a smooth curvature was generated inside the two-dimensional electron gas by etching the doped AlGaAs layer. The device was contacted at source (S) and drain (D) using an annealed layer of AuGeNi. The constriction is crossed by Ti-Au finger gates G1 and G2. A quantum dot (QD) with a quasibound state ψ is formed by applying sufficiently large negative voltages V_1 and V_2

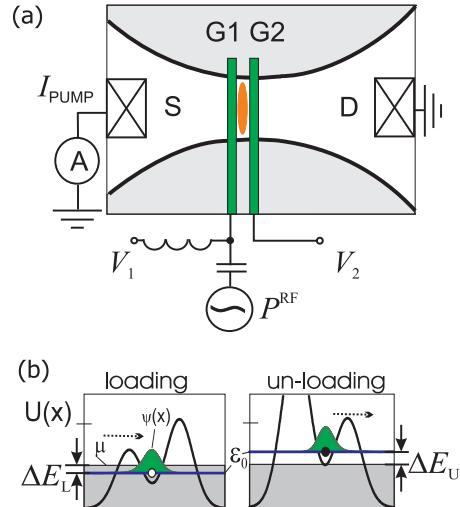


FIGURE 1. (a) Schematic of the device structure. (b) Schematic of the potential landscapes during loading and unloading as generated by the device in (a).

to G1 and G2, respectively. An additional sinusoidal signal of power P^{RF} is coupled to G1. In this way the energy ε_0 of the quasibound state drops by ΔE_L below the chemical potential μ of the leads during the first half-cycle and can be loaded with an electron [see Fig. 1(b)]. During the second half-cycle, ε_0 is raised sufficiently fast by ΔE_U above μ and can be unloaded to the right. Hence a current is driven through the sample. Details of the mechanism can be found in [6].

The pumped current I as a function of V_1 and V_2

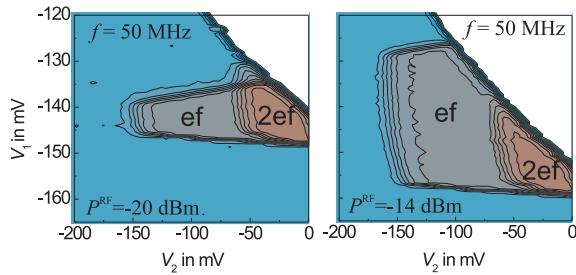


FIGURE 2. Pumping current as a function of V_1 and V_2 for two different powers. Contours correspond to variation in current of 1.5 pA

is shown in Fig. 2 for two different powers. The measurements were performed at temperature $T = 300\text{ mK}$. Contours correspond to variation in current of 1.5 pA and the plateaus to multiples of ef . The plateaus are bound for more positive V_1 by insufficient unloading to drain and for more negative V_1 by insufficient loading from source [6]. Variation in P^{RF} shifts this boundary and allows calibration of the effective modulation amplitude applied to the gate, as outlined in [7]. The step edges along V_2 are determined by escape of previously captured source-electrons back to source [8]. The white area in Fig. 2 corresponds to the region, where electrons may be loaded through the barrier at G2 and quantized pumping breaks down.

In order to determine the role of non-adiabaticity in this pumping mechanism we analyse the frequency dependence at a point in V_1 - V_2 -space where both, the constructive and destructive nature becomes visible, namely for $V_1 = -126\text{ mV}$ and $V_2 = -140\text{ mV}$. The result is shown in Fig. 3. In order to extract the effects only due to the f -dependence the voltage modulation amplitude at G1 needs to be kept constant. To this end, the specific rf-power was determined for each frequency according to [7], and the $I = ef$ - plateau was analysed. The contour corresponding to $I = 0.5ef$ is shown in the inset of Fig. 3 for each frequency ($f = 50, \dots, 500\text{ MHz}$). The contour was only traced for the relevant step-edge region.

The $I(f)$ dependence implies that the average number of pumped electrons per cycle, $n_p = I/ef$, vanishes as f is reduced, as expected when only a single voltage parameter is modulated close to the adiabatic limit [4, 9, 3, 10]. From the inset of Fig 3 one can see that this corresponds to a shift in the left border of the ef -plateau toward positive V_2 . Since this step-edge marks the transition where escape of previously captured electrons back to source is prevented [6, 8] the constructive effect of non-adiabaticity becomes visible: only when f is large enough, there will not be sufficient time for escape and the electron will contribute to I .

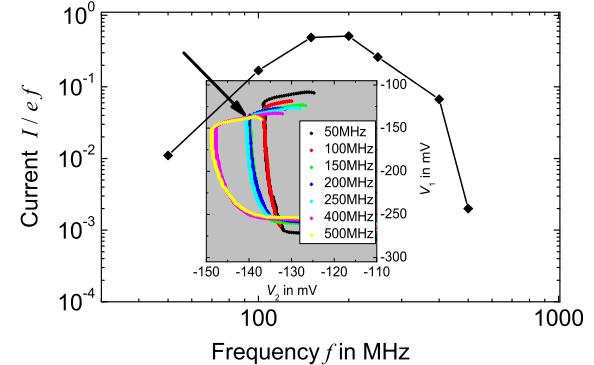


FIGURE 3. Current normalized by ef as function of frequency. Inset shows traced contours for the relevant range in V_1 - V_2 -space. The arrow indicates the voltages where the current was measured.

Increasing f beyond the optimal frequency range, n_p reduces again as predicted in [3]. From the inset of Fig 3 one can see that this corresponds to a shift in the upper border of the ef -plateau toward negative V_1 . Here the destructive nature of non-adiabaticity is illustrated: since this step-edge corresponds to insufficient unloading to drain [6] there is not sufficient time at such high frequencies to empty the dot. Consequently the electron cannot contribute to the pumping current and n_p drops.

In general, driving a quantized current by a single modulation parameter, which is only possible in the non-adiabatic regime, is of fundamental importance in the development of a scalable quantum current standard [11].

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